Final results for the SM Higgs-boson production at the Photon Collider

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Feasibility of the precise measurement of the SM Higgs-boson production cross section $\gamma\gamma \to h \to b\bar{b}$ at the Photon Collider is studied in detail for $M_h = 120$–160 GeV. All relevant experimental and theoretical issues, which could affect the measurement, are taken into account. The study is based on the realistic $\gamma\gamma$-luminosity spectra simulation. The heavy-quark background $\gamma\gamma \to Q\bar{Q}(g)$ is estimated using the NLO QCD results. Other background processes, which were neglected in earlier analyses, are also studied: $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to \tau^+\tau^-$ and light-quark pair production $\gamma\gamma \to q\bar{q}$. The contribution from the so-called overlaying events, $\gamma\gamma \to hadrons$, is taken into account. The non-zero beam crossing angle and the finite size of colliding bunches are included in the event generation. The detector simulation and realistic b-tagging are used. Criteria of event selection are optimized separately for each considered Higgs-boson mass. In spite of the significant background contribution and deterioration of the invariant mass resolution due to overlaying events, precise measurement of the Higgs-boson production cross section is still possible. For the Standard-Model Higgs boson with mass of 120 to 160 GeV the corresponding partial width $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$ can be measured with a statistical accuracy of 2.1–7.7% after one year of the Photon Collider running. The systematic uncertainties of the measurement are estimated to be of the order of 2%.

1. INTRODUCTION

The neutral Higgs boson, h, couples to the photon pair only at the loop level, through loops of all massive charged particles. In the Standard Model (SM) the dominant contribution is due to W and t loops. This loop-induced $h\gamma\gamma$ coupling is sensitive to contributions of new particles which may appear in various extensions of the SM. Hence, the precise measurement of the Higgs-boson partial width $\Gamma(h \to \gamma\gamma)$ can indicate existence of very heavy particles even if their direct production is not possible. A photon-collider option of the e^+e^- collider offers a unique possibility to measure $\Gamma(h \to \gamma\gamma)$ as the Higgs boson can be produced in the s-channel process $\gamma\gamma \to h$. The SM Higgs boson with the mass below ~ 140 GeV is expected to decay predominantly into the $b\bar{b}$ final state. Therefore, we consider the measurement of the cross section for the process $\gamma\gamma \to h \to b\bar{b}$, for $M_h = 120$–160 GeV. The aim of this study is to estimate the precision of the $\Gamma(h \to \gamma\gamma)$ measurement obtainable after one year of the Photon Collider running, taking all relevant experimental and theoretical effects into account.

2. PHOTON-PHOTON COLLISIONS

The analysis is based on the realistic $\gamma\gamma$-luminosity simulation for the Photon Collider at TESLA [1]. The simulated photon-photon events were directly used in this analysis for generation of the so-called *overlaying events* $\gamma\gamma \to hadrons$ where a proper description of the low energy tail of the spectrum was crucial. In case of other processes, for which only the high-energy part of the $\gamma\gamma$ spectrum is important, the subroutines of the COMPAZ package [2] were used. We assume that the center-of-mass energy of colliding electron beams, $\sqrt{s_{ee}}$, is optimized for the production of a Higgs boson with a given mass. Presented results are obtained for the total integrated luminosity between 400 and 500 fb^{-1}, corresponding to the luminosity expected after one year of the TESLA Photon Collider running [1].

For our analysis the longitudinal size of the collision region is most important. As this is of the order of 100 μm, we can expect that additional tracks and clusters due to overlaying events (resulting in additional vertexes, changed jet characteristics etc.) can influence the flavour-tagging algorithm and affect the event selection. Therefore, generation of all event samples used in the described analysis took into account the Gaussian smearing of primary vertex and the beams crossing angle in horizontal plane, $\alpha_c = 34$ mrad.

3. EVENT GENERATION AND SIMULATION

Total widths and branching ratios of the Higgs boson were calculated with the program HDECAY [3], where higher order QCD corrections are included. Event generation for Higgs-boson production process, $\gamma\gamma \to h \to b\bar{b}$, was done with the PYTHIA program [4]. A parton shower algorithm implemented in PYTHIA was used to generate the final-state partons. The fragmentation into hadrons was also performed using the PYTHIA program, both for Higgs-boson production and for all background event samples.

The main background for the considered signal process is the heavy-quark pair production, $\gamma\gamma \to Q\bar{Q}$. Events of 'direct', nonresonant $b\bar{b}$ production contribute to the irreducible background. In LO approximation the cross section for $J_z = 0$ is suppressed and the dominant contribution is due to the $|J_z| = 2$ state. This is very fortunate as the $\gamma\gamma$-luminosity spectrum is optimized to give highest $J_z = 0$ luminosity and the $|J_z| = 2$ component is small in the *higgs*-production region. Unfortunately, NLO corrections compensate partially the m_Q^2/s suppression and, after taking into account luminosity spectra, both contributions (for $J_z = 0$ and $|J_z| = 2$) become comparable.

The other processes $\gamma\gamma \to q\bar{q}(g)$, where $q = u, d, s, c$, and $\gamma\gamma \to \tau^+\tau^-$ contribute to the reducible background. One has to consider these processes due to the non-zero probability of wrong flavour assignment by the reconstruction procedure. Events with $c\bar{c}(g)$ in the final state have the highest mistagging probability. In comparison to the $\gamma\gamma \to b\bar{b}$ process there is an enhancement factor of $(e_c/e_b)^4 = 16$ in the $\gamma\gamma \to c\bar{c}$ cross section. It turns out that after flavour tagging both processes give similar contribution to the background. The background events due to processes $\gamma\gamma \to b\bar{b}(g)$, $c\bar{c}(g)$ were generated using the program written by G. Jikia [5], where a complete NLO QCD calculation for the production of massive quarks is performed in the massive-quark scheme.

In cases of $M_h = 150$ and 160 GeV also the pair production of W bosons, $\gamma\gamma \to W^+W^-$, is considered as a possible background. For generation of $\gamma\gamma \to W^+W^-$ events the PYTHIA program is used with polarized differential cross section formulae from [6] to obtain correct distributions for $J_z = 0$ and $|J_z| = 2$ contributions.

Because of the large cross section and huge $\gamma\gamma$-luminosity at low $W_{\gamma\gamma}$, about one $\gamma\gamma \to hadrons$ event is expected on average per bunch crossing. Such events can contribute to the background on their own and may have a great impact on the reconstruction of other events produced in the same bunch crossing, by changing their kinematical and topological characteristics.

We generate $\gamma\gamma \to hadrons$ events with PYTHIA, using luminosity spectra from the full simulation of the photon-photon collisions [1], rescaled to the chosen beam energy. For each considered e^-e^- energy, $\sqrt{s_{ee}}$, an average number of the $\gamma\gamma \to hadrons$ events per bunch crossing is calculated. Then, for every signal or background event, the $\gamma\gamma \to hadrons$ events are overlaid (added to the event record) according to the Poisson distribution. Fortunately, the $\gamma\gamma \to hadrons$ cross section is very forward-peaked. A cut on the polar angle of tracks and clusters measured in the detector can greatly reduce contribution of particles from $\gamma\gamma \to hadrons$ processes to selected events. For more details concerning $\gamma\gamma \to hadrons$ overlaying events and their influence on the reconstruction see [7].

The fast simulation program for the TESLA detector, SIMDET version 4.01 [8], was used to model the detector performance. Because two forward calorimeters, Low Angle Tagger and Low Angle Calorimeter, cannot be installed in the detector at the Photon Collider, they are not used in our simulation setup. To take into account the modified mask setup for the photon–photon option, all generator-level particles are removed from the event record, before entering the detector simulation, if their polar angle is less than $\theta_{mask} = 130$ mrad.

4. RESULTS

The contribution from overlaying events is expected to affect observed particle and energy flow mainly at low polar angles. Therefore, we introduce an angle θ_{TC} defining the region strongly contaminated by this contribution; tracks and clusters with polar angle less than θ_{TC} are not taken into account when applying energy-flow algorithm. We decided to use the value $\theta_{TC} = 0.85$ which results in the best final cross-section measurement precision. In the presented study jets are reconstructed using the Durham algorithm [9], with $y_{cut} = 0.02$.

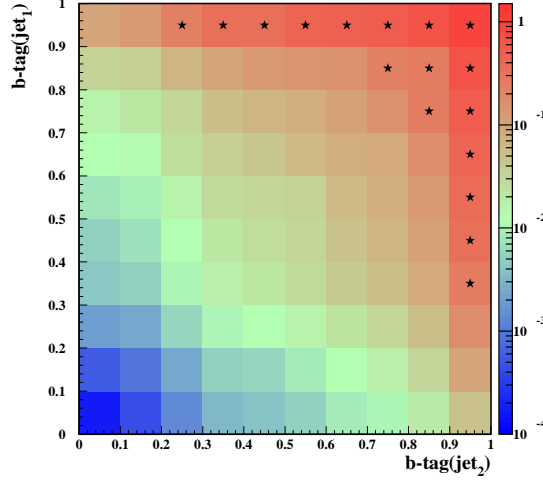Figure 1: The expected ratio of signal ($\gamma\gamma \to h \to b\bar{b}$) to background ($\gamma\gamma \to Q\bar{Q}(g)$, $Q = c, b$, and $\gamma\gamma \to q\bar{q}$, $q = u, d, s$) event distributions in the plane btag(jet$_1$) $\otimes$ btag(jet$_2$). The region which results in the best precision measurement for the cross-section measurement is indicated by stars.

Higgs-boson decay events are expected to consist mainly of two b-tagged jets with large transverse momentum and nearly isotropic distribution of the jet directions. The significant number of events ($\sim 25\%$) contains the third jet due to the real-gluon emissions which are approximated in this analysis by the parton shower algorithm, as implemented in PYTHIA. The following cuts are used to select properly reconstructed $b\bar{b}$ events coming from Higgs decay.

1. Number of selected jets should be 2 or 3.

2. The condition $|\cos\theta_{jet}| < \mathcal{C}_\theta$ is imposed for all jets in the event where θ_{jet} is the jet polar angle, *i.e.* the angle between the jet axis and the beam line. This cut should improve signal-to-background ratio as the signal is almost uniform in $\cos\theta$, while the background is peaked at $|\cos\theta| = 1$.

3. Since the Higgs bosons are expected to be produced almost at rest, the ratio of the total longitudinal momentum calculated from all jets in the event, P_z, to the total energy, E, should fulfill condition $|P_z|/E < \mathcal{C}_{P_z}$.

The cut parameter values $\mathcal{C}_\theta$ and $\mathcal{C}_{P_z}$ were optimized for each considered Higgs boson mass value to obtain the best statistical precision of the cross section measurement. For $M_h = 120$ GeV the optimized values are $\mathcal{C}_\theta = 0.725$ and $\mathcal{C}_{P_z} = 0.1$.

For b-tagging the ZVTOP-B-HADRON-TAGGER package was used [10–12], based on the the neural-network algorithm trained on the Z decays. For each jet the routine returns a "b-tag" value – the number between 0 and 1 corresponding to "b-jet" likelihood. In order to optimize the signal cross-section measurement, the two-dimensional cut on b-tag values for two jets with highest transverse momentum is used. The selection criterion is found by considering the value of the signal to background ratio S/B, where S and B denote the expected numbers of events for the signal $\gamma\gamma \to h \to b\bar{b}$ and for the sum of background contributions from processes $\gamma\gamma \to Q\bar{Q}(g)$ ($Q = c, b$) and $\gamma\gamma \to q\bar{q}$ ($q = u, d, s$), respectively. Obtained S/B distribution in the b-tag(jet$_1$)$\otimes b$-tag(jet$_2$) plane for Higgs-boson production with $M_h = 120$ GeV is shown in Fig. 1. The selection region which results in the best precision of the $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$ measurement corresponds to the condition $S/B > 0.19$ as indicated in the figure (stars).

The invariant-mass distributions for signal events passing all optimized selection cuts, before and after taking into account the overlaying events $\gamma\gamma \to hadrons$, are compared in Fig. 2 (left). The overlaying events and cuts suppressing their contribution significantly influence the mass reconstruction and result in the increase of distribution width by about 2 GeV, and in the shift of the mean value, μ, by about 3 GeV. A drop in the selection efficiency, resulting in
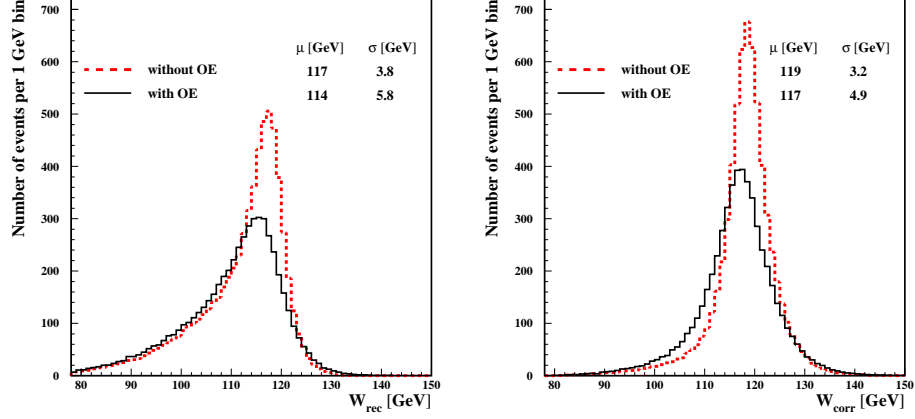
Figure 2: Reconstructed invariant-mass, W_{rec}, (left) and corrected invariant-mass, W_{corr}, (right) distributions for selected $\gamma\gamma \to h \to b\bar{b}$ events, for $M_h = 120$ GeV. Distributions obtained without and with overlaying events (OE) are compared. Results for the mean μ and dispersion σ from the Gaussian fit in the region from $\mu - 1.3\sigma$ to $\mu + 1.3\sigma$, are also shown.

the reduced number of events expected after selection cuts is also observed. The tail towards low masses is due to events with energetic neutrinos coming from semileptonic decays of D and B mesons (see [13] for more details). To compensate for this effect we use the corrected invariant mass defined as [13]:

$$W_{corr} \equiv \sqrt{W_{rec}^2 + 2P_T(E + P_T)}.$$

In Fig. 2 (right) the distributions of W_{corr} for the selected signal events, without and with overlaying events, are presented. The tail of events with invariant masses below ~ 110 GeV is much smaller than for the W_{rec} distributions (compare with the left figure). The final W_{corr} distributions for the signal and background events (with overlaying events included) are shown in Fig. 3. For $M_h = 120$ GeV the most precise measurement of the Higgs-boson production
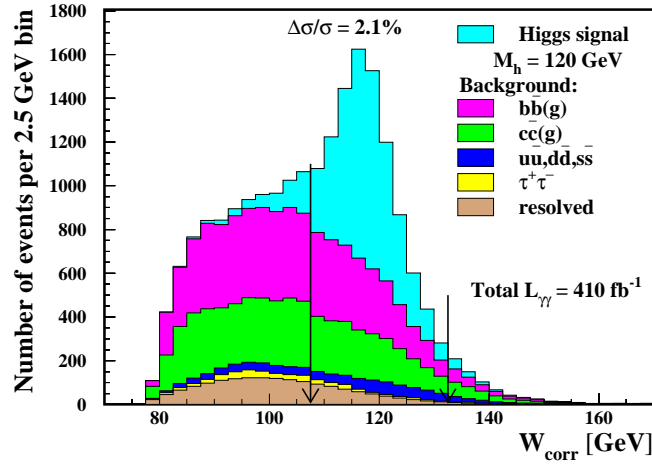

Figure 3: Distributions of the corrected invariant mass, W_{corr}, for selected $b\bar{b}$ events. Contributions of the signal, for $M_h = 120$ GeV, and of the background processes, *i.e.* $\gamma\gamma \to Q\bar{Q}(g)$ for $Q = c, b$, $\gamma\gamma \to q\bar{q}$ for $q = u, d, s$, $\gamma\gamma \to \tau^+\tau^-$, and $\gamma\gamma \to hadrons$ (as a separate contribution with *hadron-like×hadron-like* interactions only, indicated as 'resolved'), are shown separately. Arrows indicate the mass window, 107.5 to 132.5 GeV, optimized for the measurement of the $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$, which leads to the statistical precision of 2.1%.

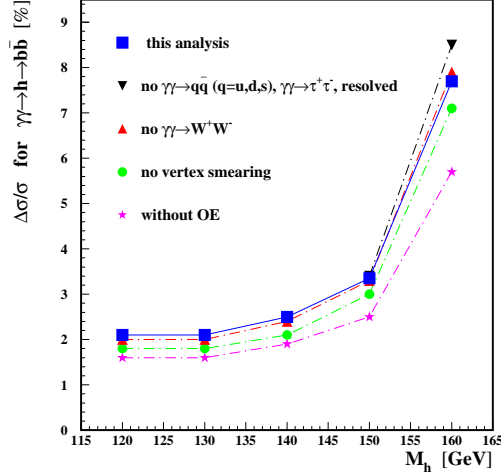Figure 4: Statistical precision of $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$ measurement for the SM Higgs boson with mass 120–160 GeV. Final results of analysis [7] are compared with our earlier results, which did not take into account all aspects of the measurement.

cross section is obtained for the mass window between 108 and 133 GeV, as indicated by arrows. In the selected W_{corr} region one expects, after one year of the Photon Collider running at nominal luminosity, about 4900 reconstructed signal events and 5400 background events (*i.e.* $\mu_S/\mu_B \approx 0.9$). This corresponds to the statistical precision of:

$$\frac{\Delta\left[\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})\right]}{\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})} = 2.1\%.$$

The systematic uncertainty of the total background contribution is estimated to be about 2%, and the $J_z = 0$ luminosity contribution will be measured with precision of around 1% [14]. Using maximal likelihood method to take these uncertainties into account we obtain precision of 2.7% for $\sigma(\gamma\gamma \to h \to b\bar{b})$ measurement at $M_h = 120$ GeV, corresponding to the systematic error of the measurement of 1.8%.

We have performed the full simulation of signal and background events for $M_h = 120$ to 160 GeV choosing optimal e^-e^- beam energy for each Higgs-boson mass. Statistical precision of $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$ measurement was estimated in each case. Results are presented in Fig. 4. For comparison, our earlier results obtained without overlaying events, without various background contributions or without distribution of interaction point are also shown. For $M_h = 160$ GeV, after the full optimization of the selection cuts, better precision is obtained than in earlier analyses, which did not take into account some background contributions.

5. SUMMARY

One of the measurements crucial for understanding of the Higgs sector and for the verification of the particle physics models is the measurement of $\Gamma(h \to \gamma\gamma)$. The Photon Collider, which has been proposed as an extension of the e^+e^- linear collider project, is considered the best place to do this measurement.

We present the first fully realistic estimates for the precision of $\gamma\gamma \to higgs \to b\bar{b}$ cross-section measurement at the Photon Collider with parameters of the TESLA project. The analysis is based on the realistic $\gamma\gamma$-luminosity spectrum simulation. Due to the high beam intensity, resulting in high $\gamma\gamma$-luminosity per bunch crossing, the contribution of overlaying events $\gamma\gamma \to hadrons$ turns out to be sizable and affects the event reconstruction. Crossing angle between beams resulting in the significant broadening of the interaction region is also taken into account. These two factors have significant impact on the performance of the b-tagging algorithm. It is shown that the contamination of

$\gamma\gamma \to hadrons$ overlaying events in the signal can be reduced by rejecting low-angle tracks and clusters in the event. Additional cuts are proposed to suppress contributions from other background sources.

After optimizing selection cuts and applying correction for escaping neutrinos from D- and B-meson decays the quantity $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$, for the SM Higgs boson with mass around 120 GeV, can be measured with the precision of about 2% already after one year of the Photon Collider running. The systematic uncertainties of the measurement are estimated to be of the order of 2%. The statistical precision of the measurement decreases up to 7.7% for the SM Higgs boson with mass $M_h = 160$ GeV. For higher masses of the SM Higgs boson other decay channels are expected to give better precision of $\Gamma(h \to \gamma\gamma)$ measurement, see *e.g.* [15]. Presented results are consistent with earlier studies [16, 17], which however did not take into account all aspects of the measurement considered here.

The measurement discussed in this paper can be used to derive the partial width $\Gamma(h \to \gamma\gamma)$, taking $\mathrm{BR}(h \to b\bar{b})$ value from precise measurement at the e^+e^- International Linear Collider. With 2% accuracy on $\Gamma(h \to \gamma\gamma)\mathrm{BR}(h \to b\bar{b})$, as obtained in this analysis, and assuming $\mathrm{BR}(h \to b\bar{b})$ will be measured to 1.5% [18], Higgs-boson partial width $\Gamma(h \to \gamma\gamma)$ can be extracted with accuracy of about 2.5%. With this precision the measurement will be sensitive to the deviations from the SM coming from loop contributions of new heavy charged particles. For example, heavy charged *higgs* contribution in the SM-like 2HDM is expected to change $\Gamma(h \to \gamma\gamma)$ by 5–10% [19]. Using in addition the result from the e^+e^- Linear Collider for $\mathrm{BR}(h \to \gamma\gamma)$ [20], one can also extract the total width Γ_h with precision of about 10%.

Acknowledgments

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